Rare and Very Rare Decays of Charmed Mesons and Charmonia at BESIII

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Rare decays of charm

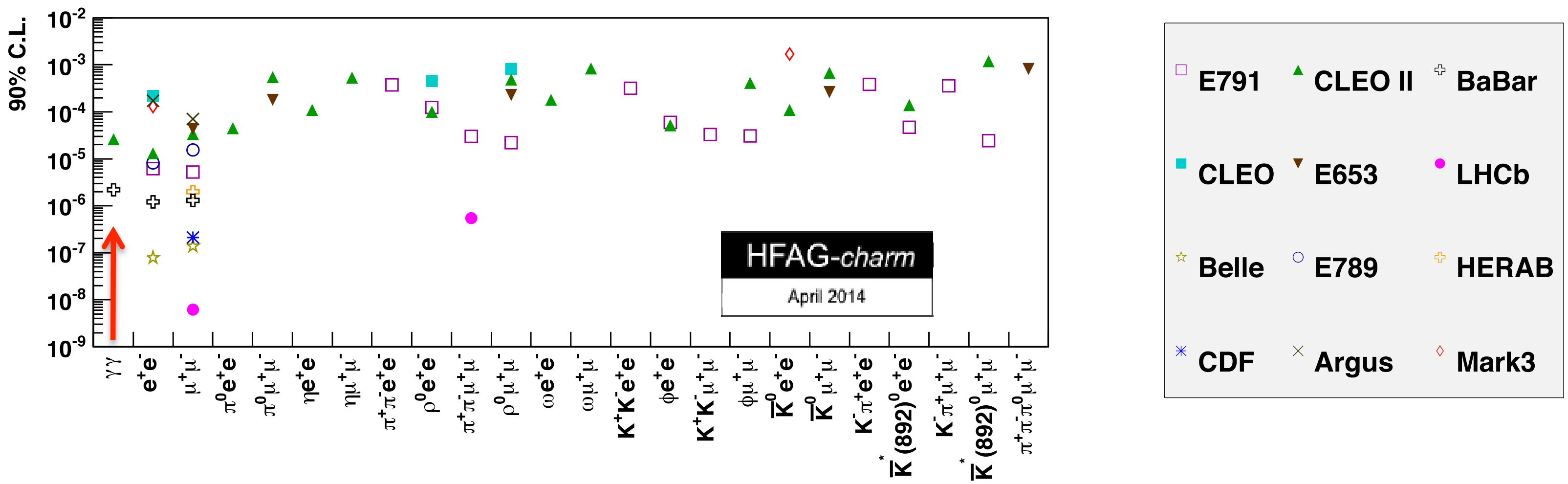
- Flavor Changing Neutral Current (FCNC) processes are very rare in SM being suppressed by absence of tree level diagrams and by GIM mechanism.

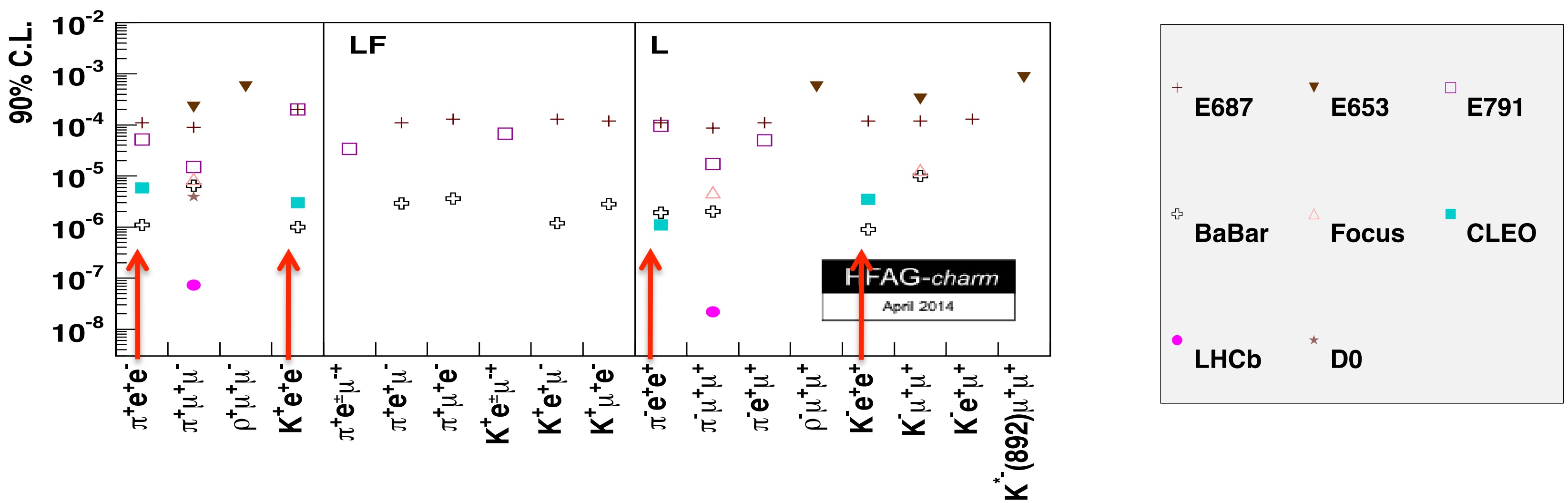
- FCNC in charm are even more suppressed due to absence of high mass down-type quark.

- Many new physics scenarios can therefore contribute enhancing these processes with new particles running in the loops or even at tree level.

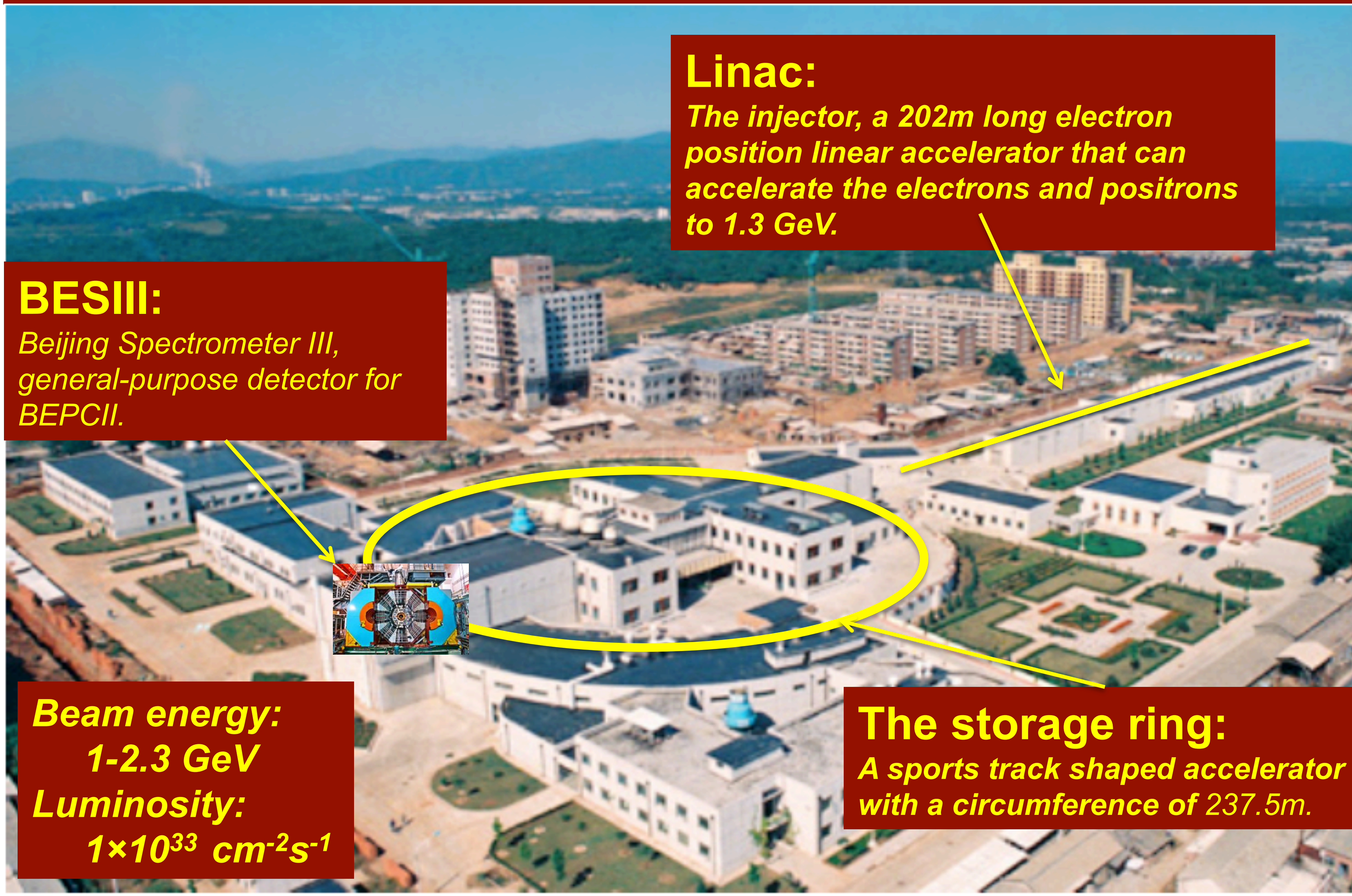
- Some models predict enhancements in the up sector only.

Experimental status up to 2014





Beijing Electron Positron Collider II (BEPCII)



Linac:

The injector, a 202m long electron position linear accelerator that can accelerate the electrons and positrons to 1.3 GeV.

BESIII:

Beijing Spectrometer III, general-purpose detector for BEPCII.

Beam energy:

1-2.3 GeV

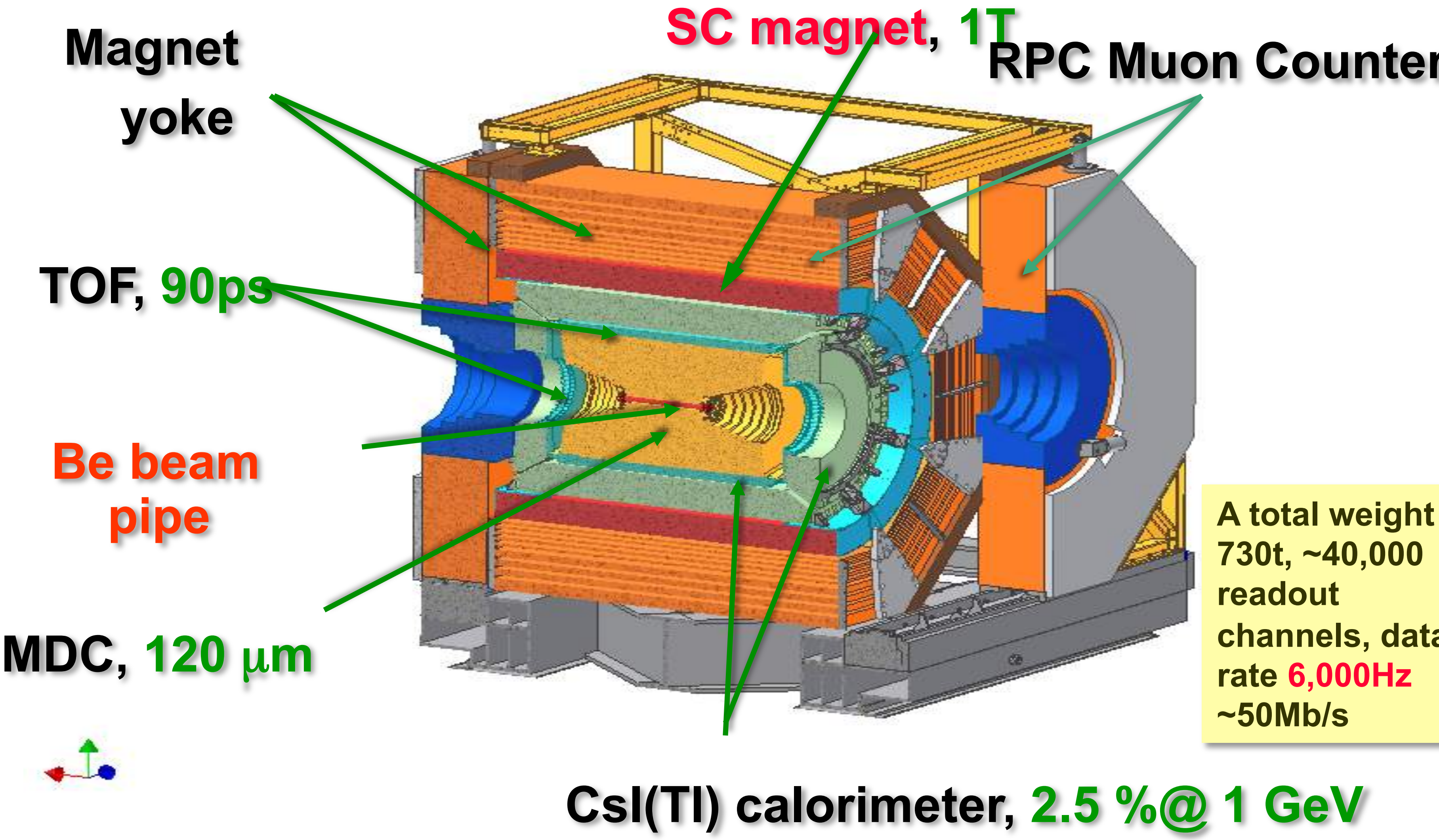
Luminosity:

1×10^{33} $cm^{-2}s^{-1}$

The storage ring:

***A sports track shaped accelerator with a circumference of** 237.5m.*

The BESIII Detector



A total weight of 730t, ~40,000 readout channels, data rate 6,000Hz ~50Mb/s

BESIII Collaboration

US (5)

Univ. of Hawaii
Carnegie Mellon Univ.
Univ. of Minnesota
Univ. of Rochester
Univ. of Indiana

Europe (13)

Germany: Univ. of Bochum, Univ. of Giessen, GSI
Univ. of Johannes Gutenberg
Helmholtz Ins. In Mainz
Russia: JINR Dubna; BINP Novosibirsk
Italy: Univ. of Torino, Univ. of Ferrara, Frascati Lab
Netherland: KVI/Univ. of Groningen
Sweden: Uppsala Univ.
Turkey: Turkey Accelerator Center

Korea (1)

Seoul Nat. Univ.

Japan (1)

Tokyo Univ.

Pakistan (2)

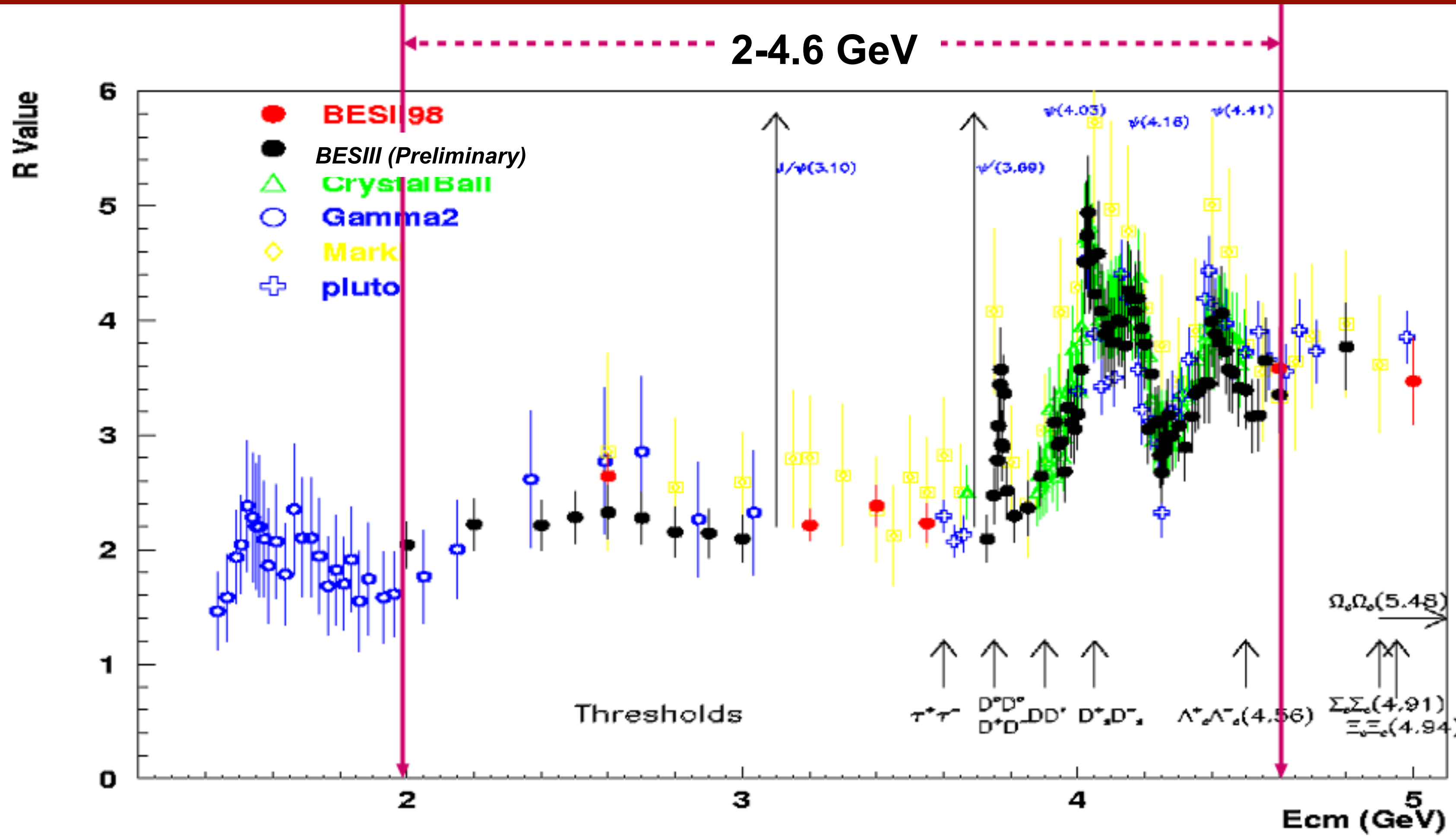
Univ. of Punjab
COMSAT CIIT

China(31)

IHEP, CCAST, GUCAS, Shandong Univ., Univ. of Sci. and Tech. of China
Zhejiang Univ., Huangshan Coll.
Huazhong Normal Univ., Wuhan Univ.
Zhengzhou Univ., Henan Normal Univ.
Peking Univ., Tsinghua Univ. ,
Zhongshan Univ.,Nankai Univ.
Shanxi Univ., Sichuan Univ., Univ. of South China
Hunan Univ., Liaoning Univ.
Nanjing Univ., Nanjing Normal Univ.
Guangxi Normal Univ., Guangxi Univ.
Suzhou Univ., Hangzhou Normal Univ.
Lanzhou Univ., Henan Sci. and Tech. Univ.
Beihang Univ., Beijing Petrol Chemical Univ.

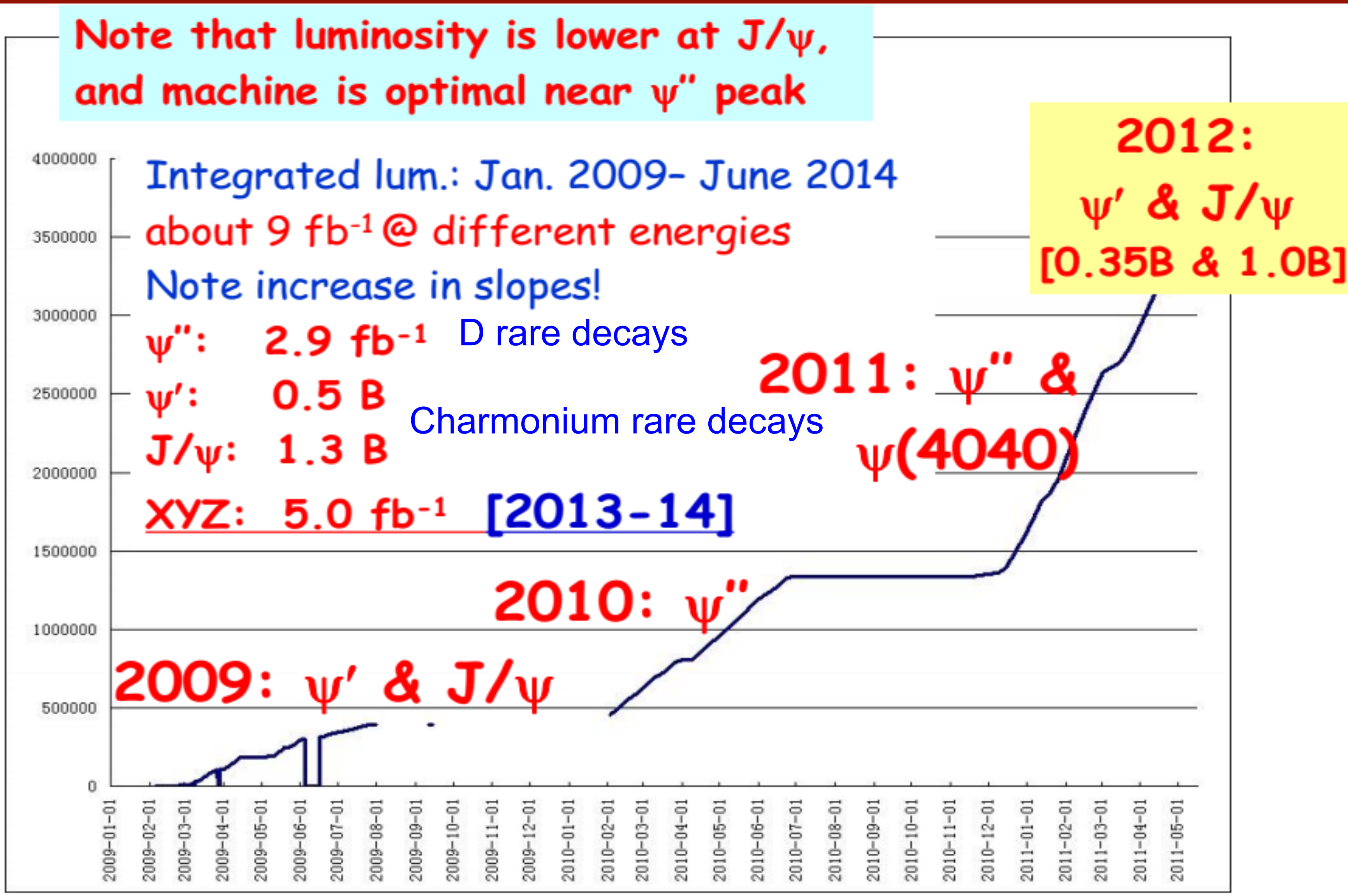
~400 members
53 institutions from 11 countries

E_{cm} range @ BESIII/BEPCII



Physics programs at BESIII include light-hadron and charmonium spectroscopy, electroweak and strong physics at the charm scale, tau-physics, R value measurement and searches for rare processes.

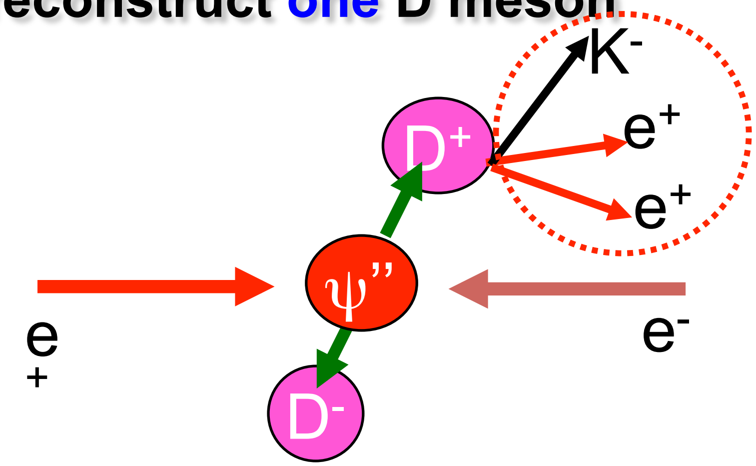
Data collected over time



Single Tag vs. Double Tag

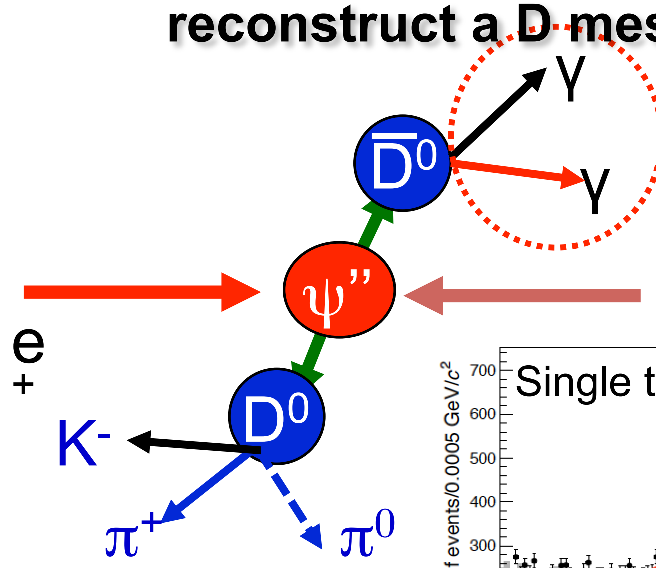
Singly tagged D meson:

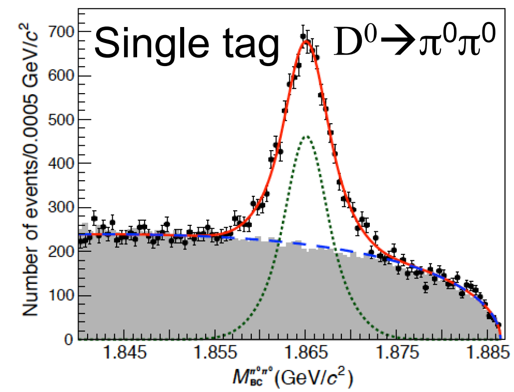
reconstruct one D meson

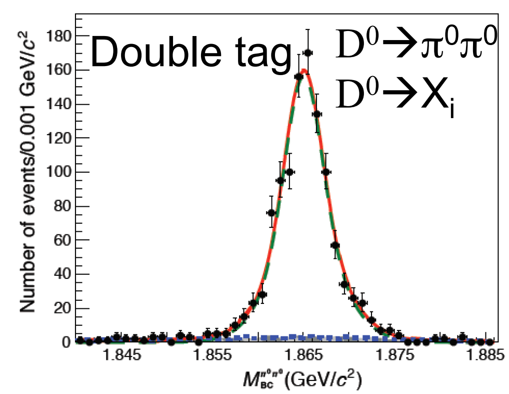


Doubly tagged D meson:

reconstruct a D meson pair







	Statistics （charged/ neutral）	Backgrou nd
Single Tag	1.7×10^7 / 2.1×10^7	high
Double Tag	1.6×10^6 / 2.8×10^6	low

$D^0 \to \gamma\gamma$

- FCNC mode, forbidden at tree level

→ Larger GIM suppression

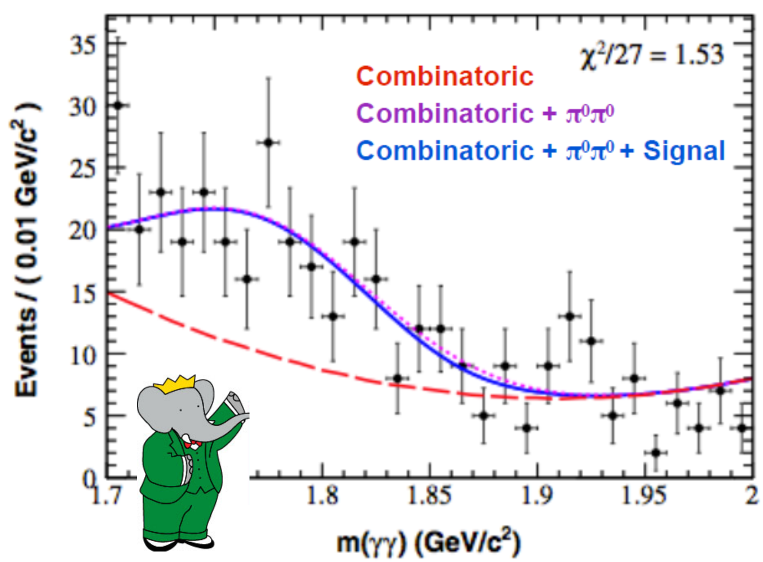
→ Short distance: BF~10^{-11} [PRD66 (2002) 014009]

→ Long distance due to VMD: BF~10^{-8} [PRD66 (2002) 014009]

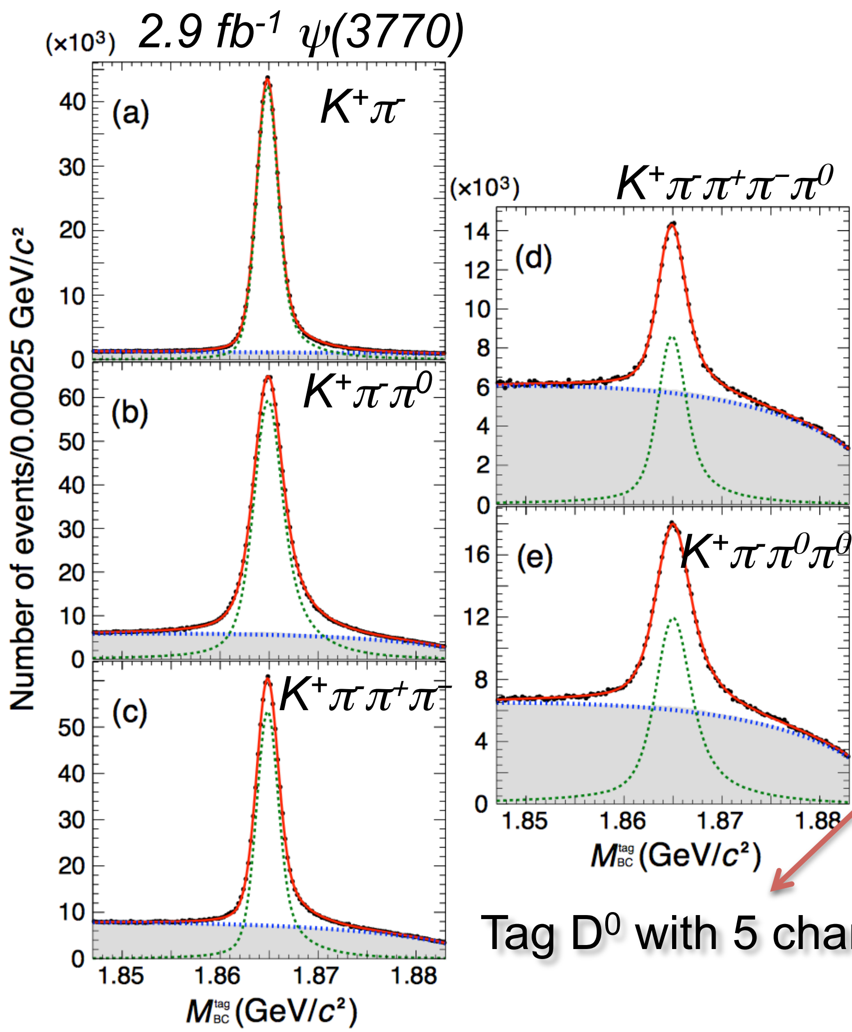
→ MSSM up to BF~10^{-6} [PLB500(2001)304], i.e. $c \to u\gamma$ via gluino exchange

- BaBar (PRD85, 091107(R) (2012)):
  - Reconstruct through $D^{*+} \to D^0(\to \gamma\gamma)\,\pi^+$, normalized by $D^{*+} \to D^0(\to K_S\pi^0)\,\pi^+$.
  - Peaking background from $D^0 \to \pi^0\pi^0$.
  - $B(D^0 \to \gamma\gamma) < 2.2\times10^{-6}$ @ 90% C.L.

Phys. Rev. D 85 (2012) 091107R



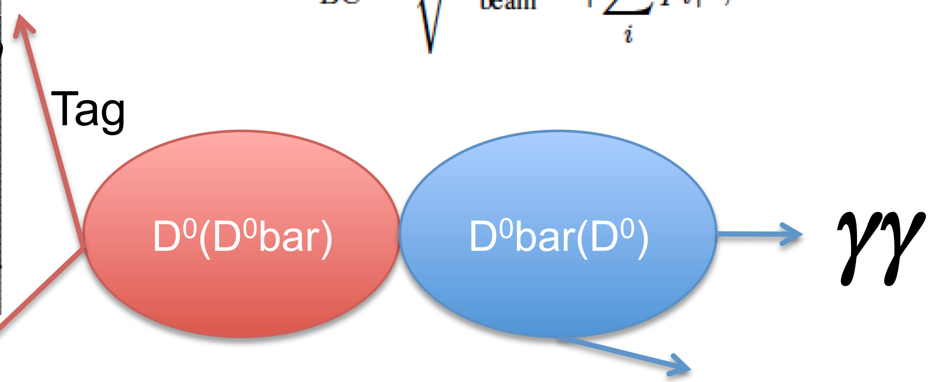
$D^0 \to \gamma\gamma$ with double tag method



The $\psi(3770)$ resonance is below the threshold for $D\bar{D}\pi$ production, so the events from $e^+e^- \to \psi(3770) \to D\bar{D}$ have D mesons with energies equal to the beam energy ($E_{\rm beam}$) and known momentum. Thus, to identify $\bar{D}^0$ candidate, we define the two variables ΔE and $M_{\rm BC}$, the beam-constrained mass:

$$\Delta E \equiv \sum_i E_i - E_{\rm beam},$$

$$M_{\rm BC} \equiv \sqrt{E_{\rm beam}^2 - |\sum_i \vec{p}_i|^2},$$

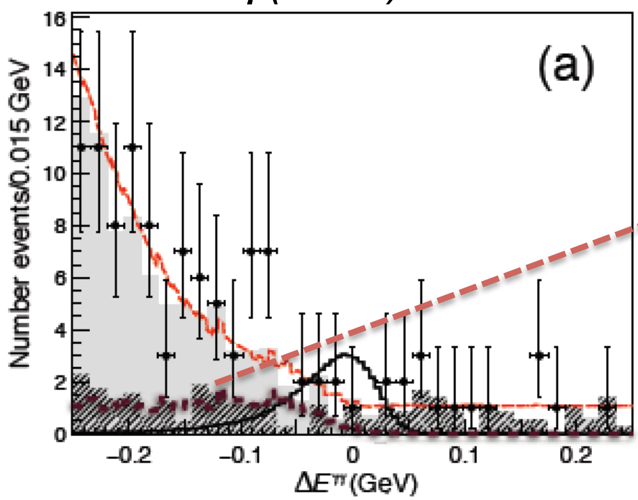


Tag D^0 with 5 channels on tag side.

Cut on M_{BC} on the tag side, and search for $\gamma\gamma$ in $\Delta E_{\gamma\gamma}$ on the recoiling side

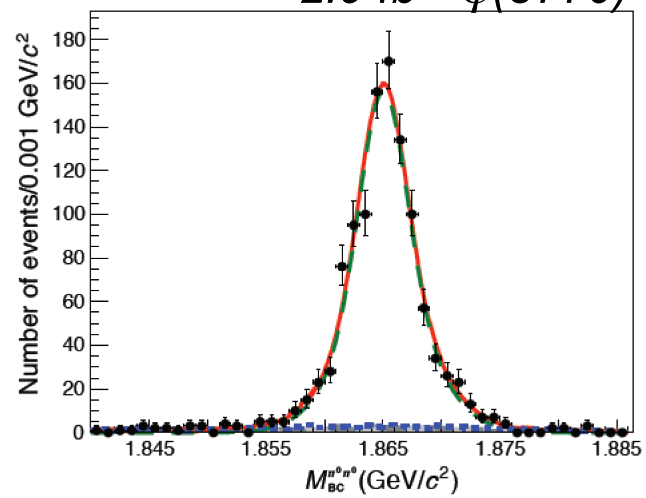
$D^0 \to \gamma\gamma$ with double tag method

2.9 fb^{-1} ψ(3770)

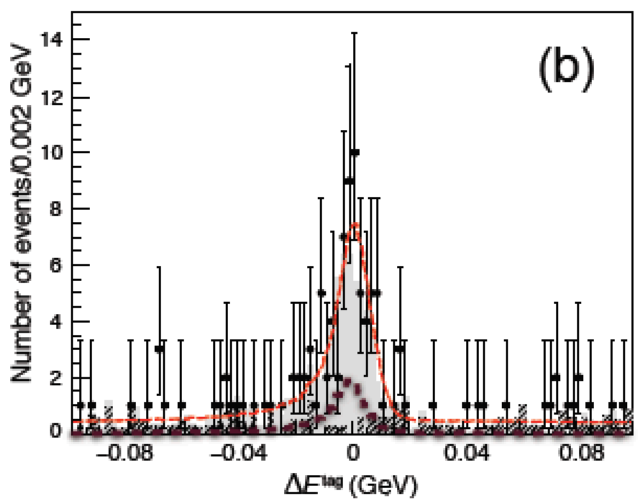


Major background $D^0 \to \pi^0\pi^0$ is determined in data with similar double-tag method.

2.9 fb^{-1} ψ(3770)



$B(D^0 \to \pi^0\pi^0) = (8.24 \pm 0.21 \pm 0.30) \times 10^{-4}$



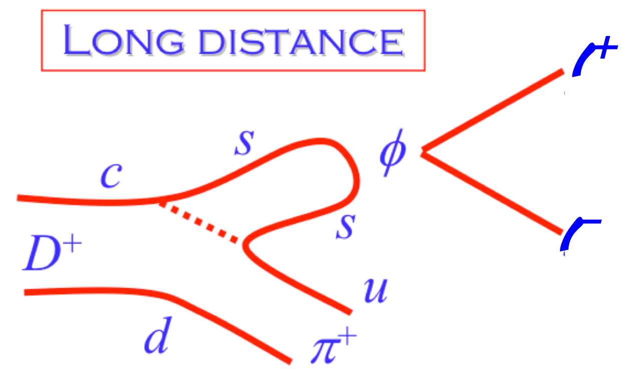
2-D fit to ΔE in both tag side and γγ sides to determine $D^0 \to \gamma\gamma$ yield.

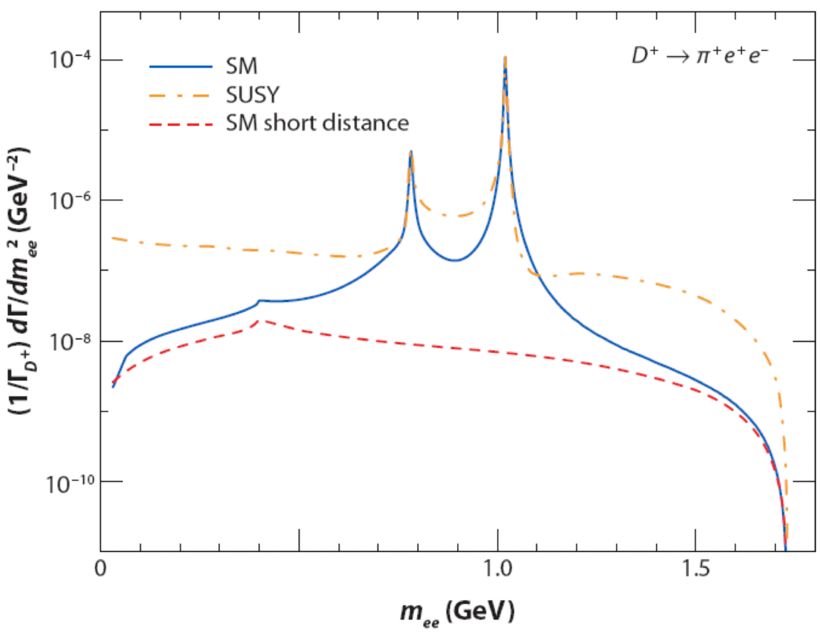
$$B(D^0 \to \gamma\gamma) < 3.8 \times 10^{-6}$$

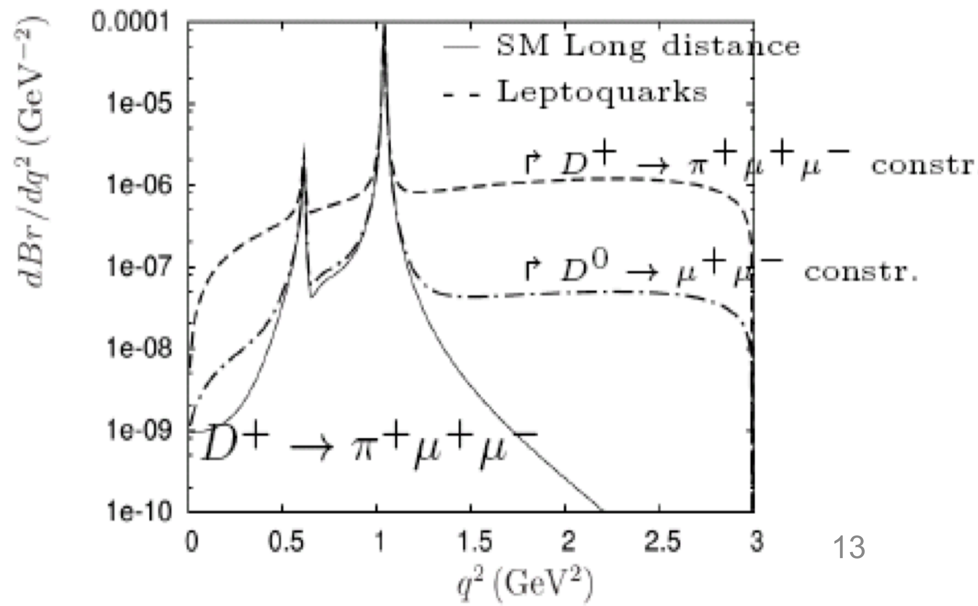
consistent with BaBar result,
will update with a 4X larger sample.

$D^+ \rightarrow h^{+/-}e^+e^{-/+}$

- Short distance contributions heavily suppressed by GIM mechanism.
- SM rate dominated by long distance contribution via resonances: $D \rightarrow XV \rightarrow Xl^+l^-$, $V=\phi,\rho,\omega$
- Although SM BRs around resonances is at 10^{-6}, non-resonance part is at 10^{-8} → outside of the resonances, there is big room to discover new physics contribution.







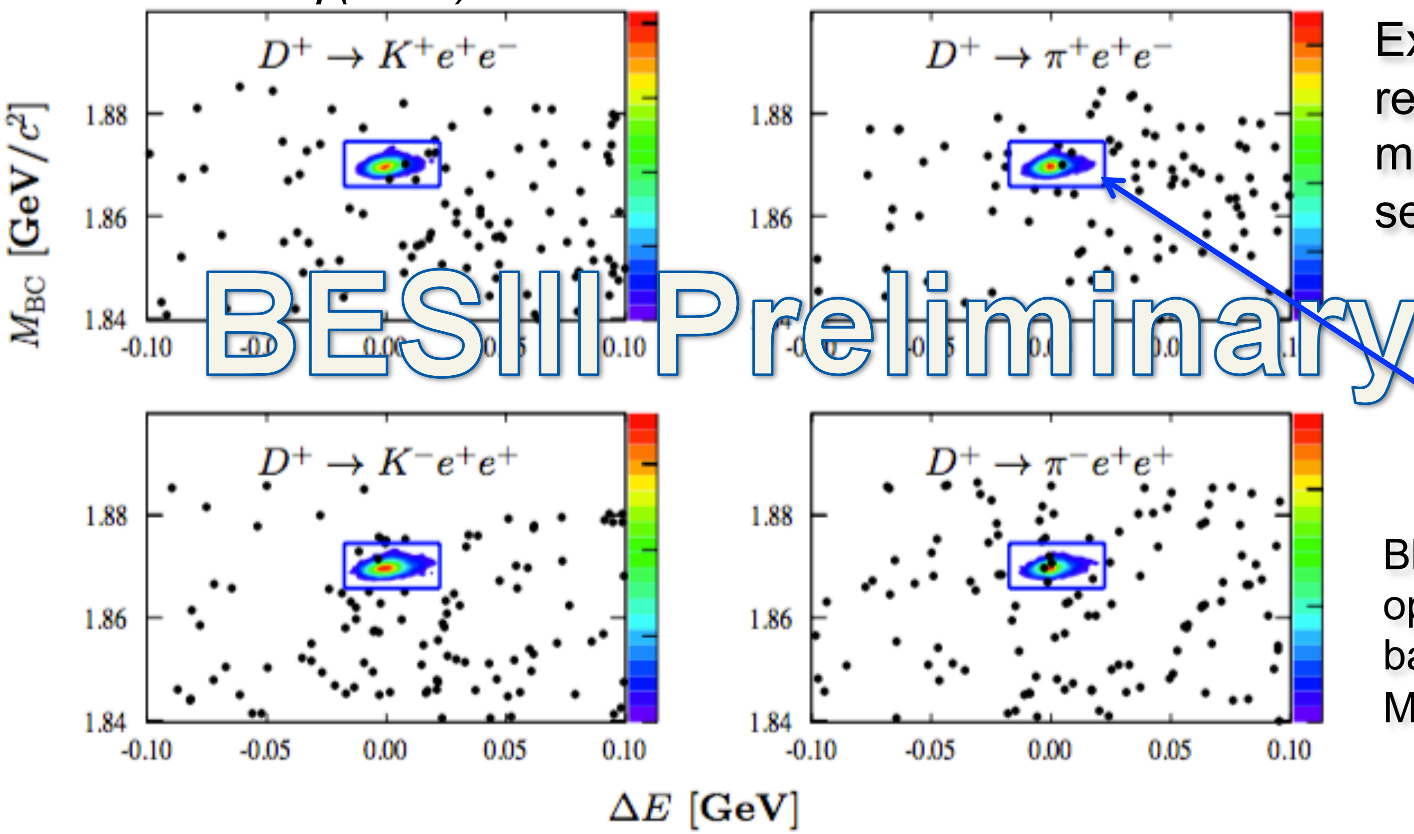
Current status

$\mathcal{B}(D^+ \to) \setminus [\times 10^{-6}]$	$K^+e^+e^-$	$K^-e^+e^+$	$\pi^+e^+e^-$	$\pi^-e^+e^+$
CLEO[1]	-	-	2600	-
MARK2[2]	4800	9100	2500	4800
E687[3]	200	120	110	110
E791[4]	200	-	52	96
CLEO[5]	3.0	3.5	5.9	1.1
Babar[6]	1.0	0.9	1.1	1.9
PDG[7]	1.0	0.9	1.1	1.1

[1] P. Haas et al. (CLEO Collaboration), Phys. Rev. Lett. 60, 1614 (1988).
[2] A. J. Weir et al. (MarkII Collaboration), Phys. Rev. D 41, 1384 (1990).
[3] P. L. Frabetti et al. (E687 Collaboration), Phys. Lett. B 398, 239 (1997).
[4] E. M. Aitala et al. (E791 Collaboration), Phys. Lett. B 462, 401 (1999).
[5] P. Rubin el al. (CLEO Collaboration), Phys. Rev. D 82, 092007 (2010).
[6] J. P. Lees el al. (BaBar Collaboration), Phys. Rev. D 84, 072006 (2011).
[7] K. A. Olive et al. (Particle Data Group), Chin. Phys. C, 38, 090001 (2014).

$D^+ \to h^{+/-}e^+e^{-/+}$ with single tag method

2.9 fb^{-1} $\psi(3770)$



Exclude ϕ meson region in invariant mass of e^+e^- for NP search.

Blinding signal region, optimize cuts and study backgrounds based on MC and sideband data.

Scatter plots for M_{BC} versus ΔE, where the signal boxes are shown as a blue rectangle. The contours are determined from MC simulation to enclose 84% of signal events for each channel.

$D^+ \to h^{+/-}e^+e^{-/+}$ with single tag method

	N^{data}_{inside}	$N^{data}_{outside}$	f_{scale}	ϵ [%]	Δ_{sys} [%]	s_{90}	$\mathcal{B}[\times 10^{-6}]$
$D^+ \to K^+e^+e^-$	5	69	0.08 ± 0.01	22.53	5.4	19.4	< 1.2
$D^+ \to K^-e^+e^+$	3	55	0.08 ± 0.01	24.08	6.1	10.2	< 0.6
$D^+ \to \pi^+e^+e^-$	3	65	0.09 ± 0.02	25.72	5.9	4.2	< 0.3
$D^+ \to \pi^-e^+e^+$	5	68	0.06 ± 0.02	28.08	6.8	20.5	< 1.2

Where s_{90} is estimated with a profile likelihood method, **TROLKE** program [NIM, A551 (2005) 493], incorporating systematic uncertainties and detection efficiencies.

Our result is better than the results from CLEO and comparable with Babar.

Summary for rare charm decays

- With the world largest threshold D meson sample, BESIII got the (leading) upper limits on $D^0 \rightarrow \gamma\gamma$, $D^+ \rightarrow hee$ decays.
- Present upper limits still above SM predictions, no NP effects have been seen yet.
- BESIII will take 3 fb^{-1} data at 4.17 GeV in 2016 and 10 fb^{-1} more data at 3.773 GeV in the future.
- More results can be expected next year

Rare Charmonium Decays

- Semileptonic weak decays:

  $\psi(nS) \to D_q l\nu,\ \psi(nS) \to \bar{D}^{0/*} l^+ l^-$

- Two-body weak hadronic decays

  $J/\psi \to D_s^- \pi^+ / K^+ + c.c., J/\psi \to D_s^{(*)+} \rho^- / K^{*-} + c.c., \ldots$

- C/P violation decays

  $J/\psi \to \gamma\gamma, \gamma V, VV, PP$

- Lepton flavor violation decays

  $J/\psi \to e\mu, e\tau, \mu\tau$

Invisible decays and other quantities violated decays also can be searched, such as baryon number

The results shown in this report are based on **2.25×10^8** J/ψ or **1.06×10^8** ψ(3686) events accumulated with BESIII. All upper limit Brs are given at the **90% C.L.**

SM predicts total BR of J/ψ weak decays is (2 ~ 4) × 10^{-8} , BESIII currently have 2.25×10^8 J/ψ events and will take 10^{10}. This means BESIII will have ~400 weak decays for the predicted SM BR.

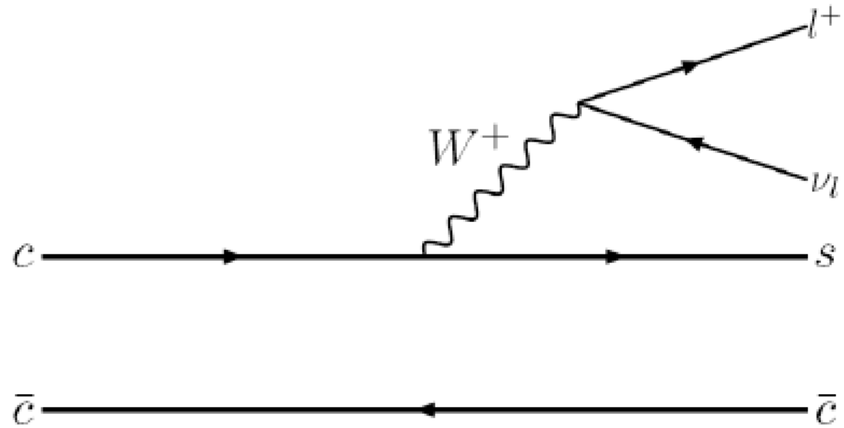
Semileptonic weak decays

Within Standard Model

QCD sum rules: ~10^{-10}

New Physics

Top color model
Minimal Supersymmetric SM
Two-Higgs-doublet model



Feynman diagram for $J/\psi \to D_s^{(*)-} l^+ \nu$ at the tree level

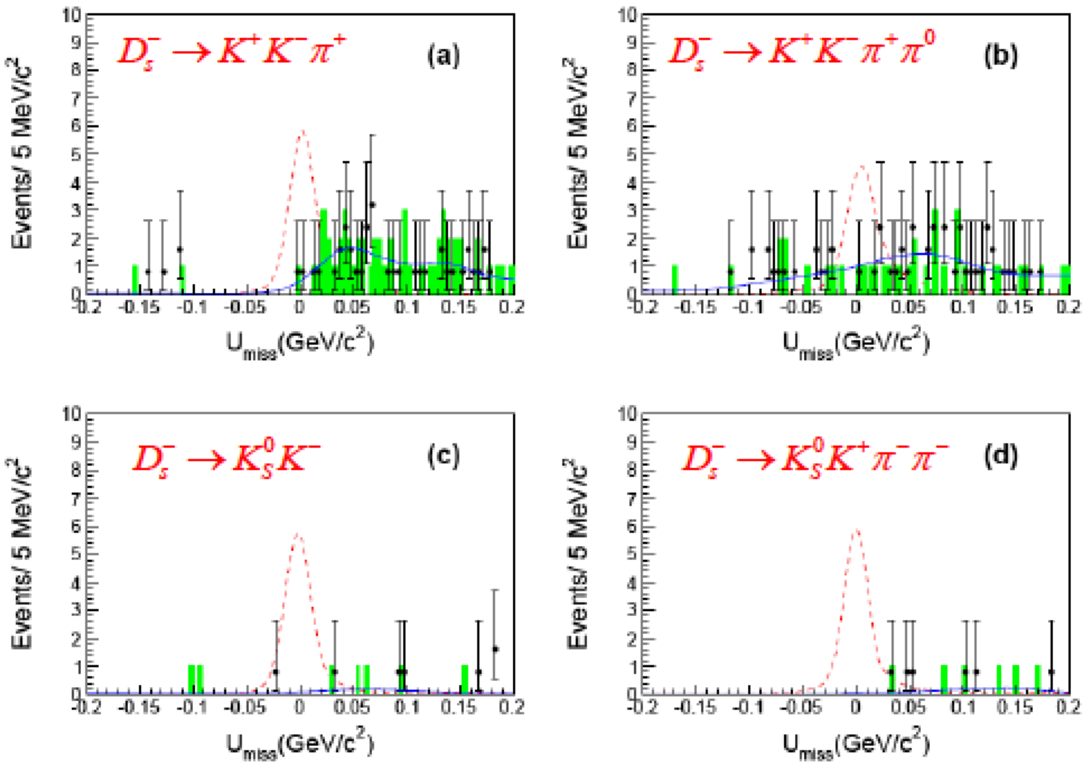
$$\frac{Br(J/\psi \to D_s^* l\nu)}{Br(J/\psi \to D_s l\nu)} \approx 1.5 \sim 3.1$$

Z. Phys. C. 62, 271
Eur. Phys. J. C. 54, 107

Semileptonic weak decays

2.25×10^8 J/ψ

Phys. Rev. D 90, 112014 (2014)



D_s^- is reconstructed by four channels and the combined likelihood is calculated:

$$\mathcal{L}_k = \prod_{i=1}^{N_k} \frac{N_{\text{total}}\mathcal{B}_k\epsilon_k\mathcal{P}_{i,k}^{\text{sig}} + N_k^{\text{bkg}}\mathcal{P}_{i,k}^{\text{bkg}}}{N_{\text{total}}\mathcal{B}_k\epsilon_k + N_k^{\text{bkg}}}$$

$$\frac{\int_0^{N_{\text{total}}^{\text{up}}} \mathcal{L}(N_{\text{total}})dN_{\text{total}}}{\int_0^{\infty} \mathcal{L}(N_{\text{total}})dN_{\text{total}}} = 0.90$$

$$E_{\text{miss}} = E_{J/\psi} - E_{D_s^-} - E_{e^+} \qquad \vec{p}_{\text{miss}} = \vec{p}_{J/\psi} - \vec{p}_{D_s^-} - \vec{p}_{e^+} \qquad U_{\text{miss}} = E_{\text{miss}} - |\vec{p}_{\text{miss}}|$$

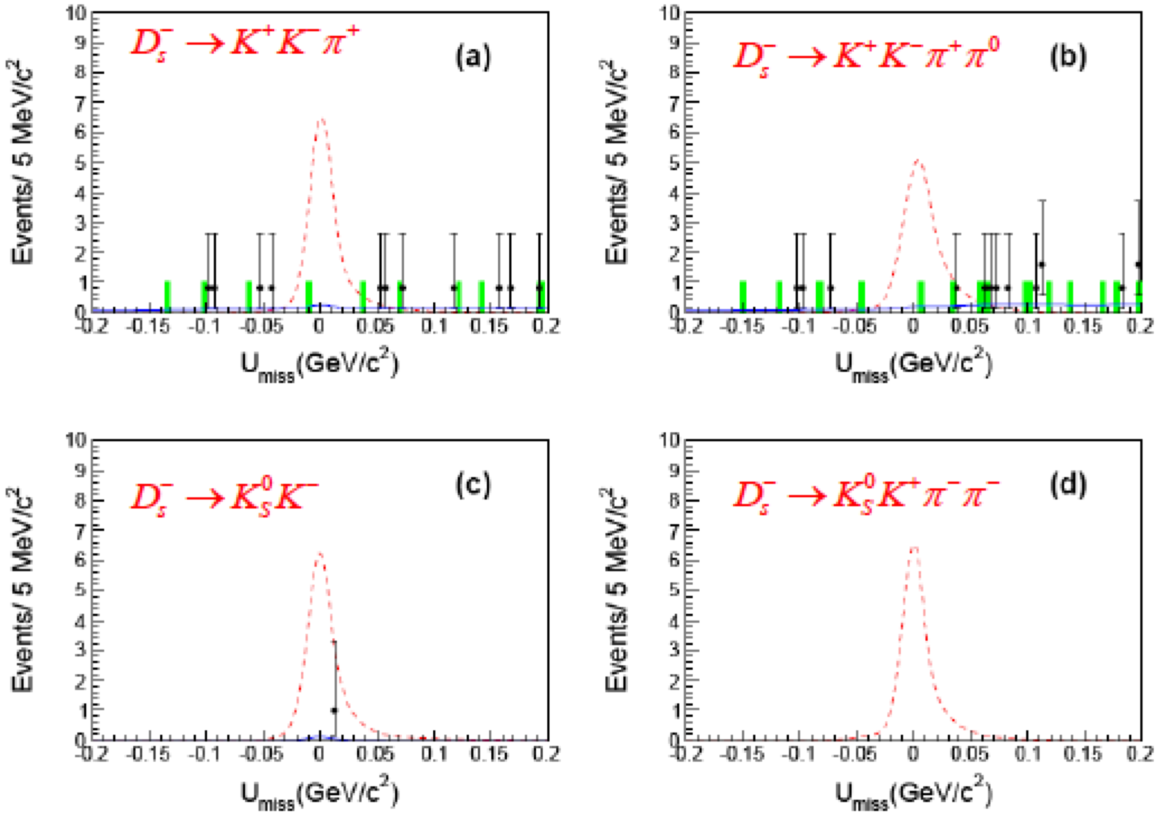
$$Br(J/\psi \to D_s^- e^+ \nu_e + c.c.) < 1.3\times 10^{-6}$$

$< 3.6\times 10^{-5}$
(best results before)

Semileptonic weak decays

2.25×10^8 J/ψ

Phys. Rev. D 90, 112014 (2014)



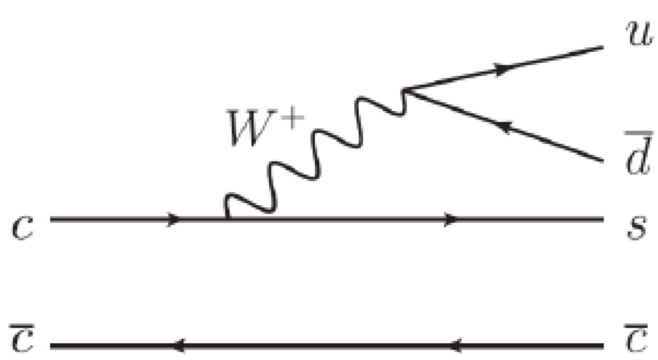
D_s^{*-} is reconstructed by

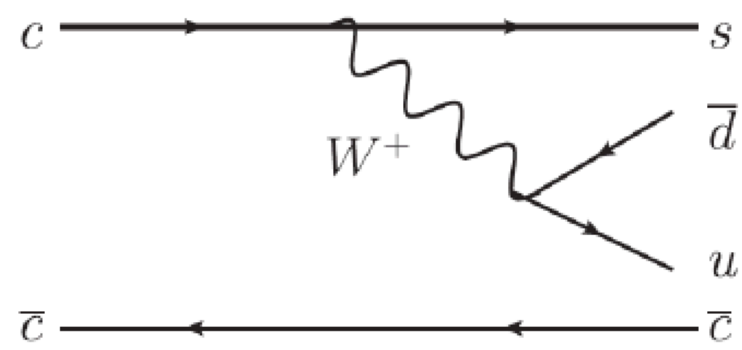
$$D_s^{*-} \to \gamma D_s^-$$

The same analysis method as $D_s e\nu$

$$Br(J/\psi \to D_s^{*-}e^+\nu_e + c.c.) < 1.8\times10^{-6}$$

Two-body hadronic weak decays





Within Standard Model

Factorization model: $\sim 10^{-9} \sim 10^{-10}$

New Physics : $\sim 10^{-5} \sim 10^{-6}$

Top color model
Minimal Supersymmetric SM
Two-Higgs-doublet model

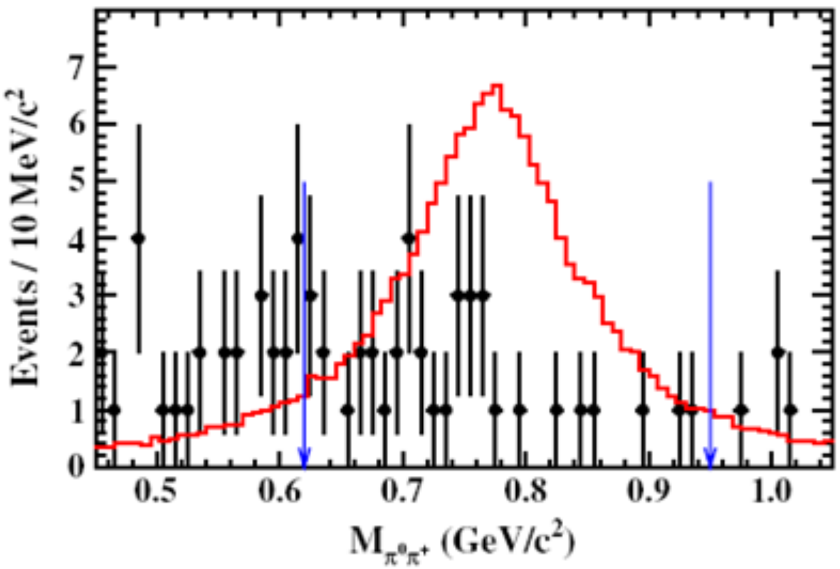
$$\frac{Br(J/\psi \to D_s^+ \rho^-)}{Br(J/\psi \to D_s^+ \pi^-)} \approx 5$$

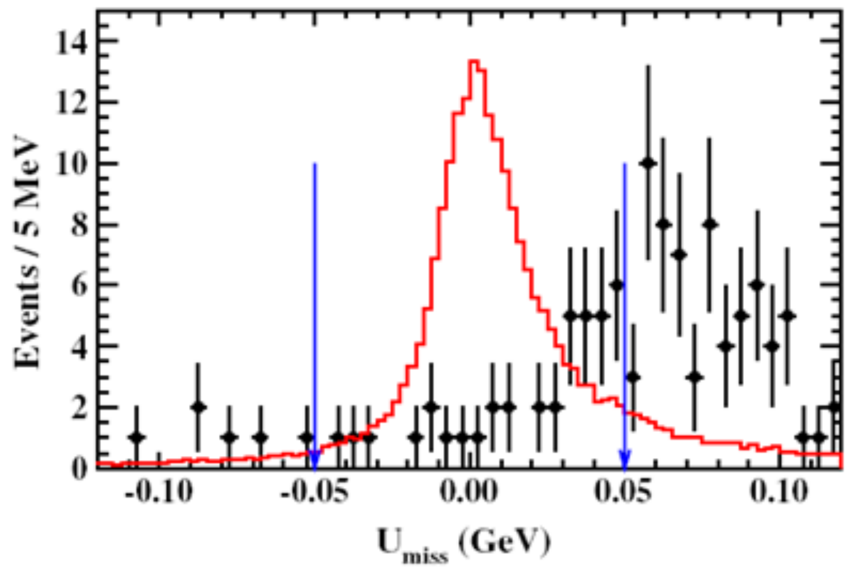
$$\frac{Br(J/\psi \to D^0 K^{*0})}{Br(J/\psi \to D_s^+ \rho^-)} \approx 0.1$$

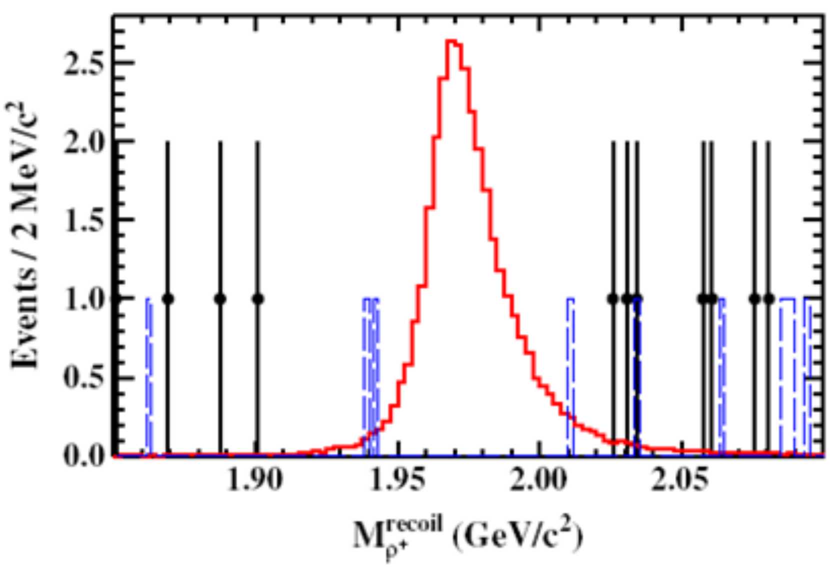
Phys. Lett. B 252, 690

Two-body hadronic weak decays

Phys. Rev. D 89, 071101(2014)







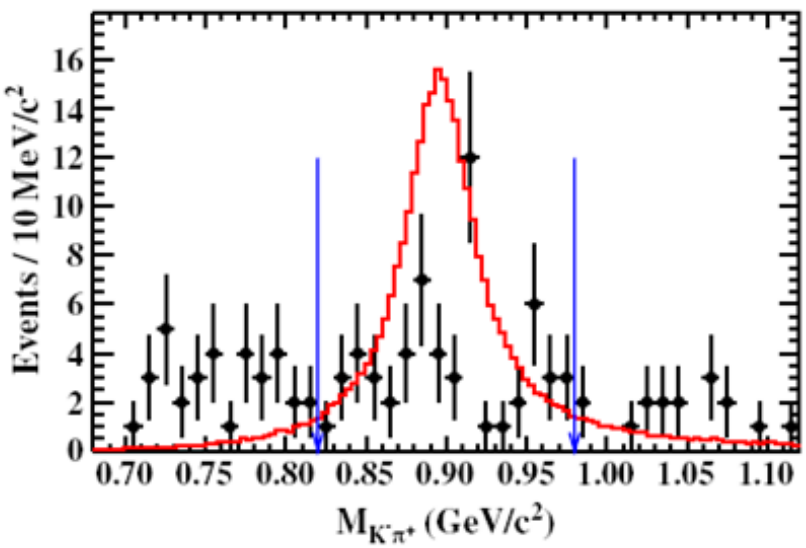
$$J/\psi \to D_s^- \rho^+$$

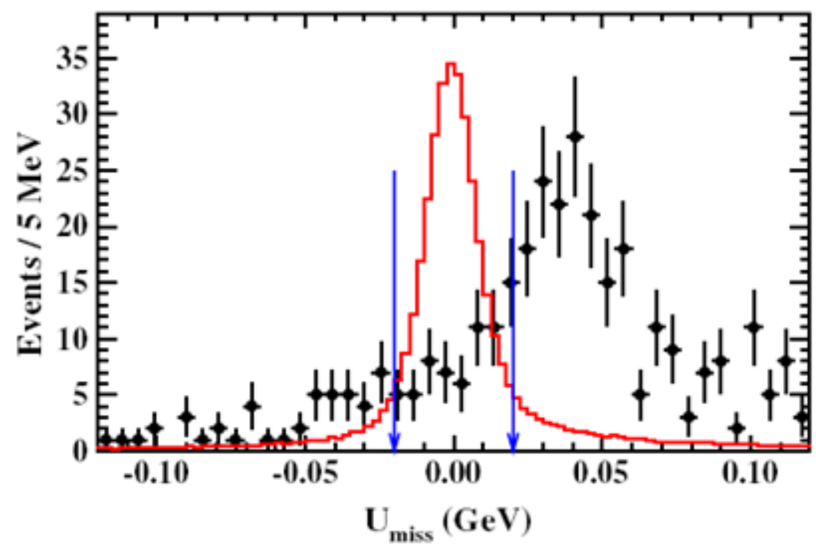
$$D_s^- \to \phi e^- \overline{\nu}_e, \phi \to K^+ K^-$$

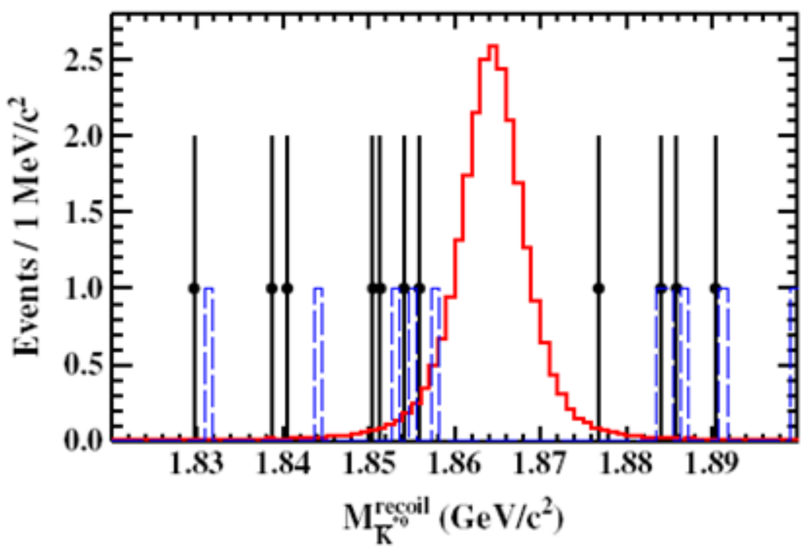
$$Br(J/\psi \to D_s^- \rho^+) < 1.3 \times 10^{-5}$$

Two-body hadronic weak decays

Phys. Rev. D 89, 071101(2014)







$$J/\psi \to \bar{D}^0 \bar{K}^{*0}$$

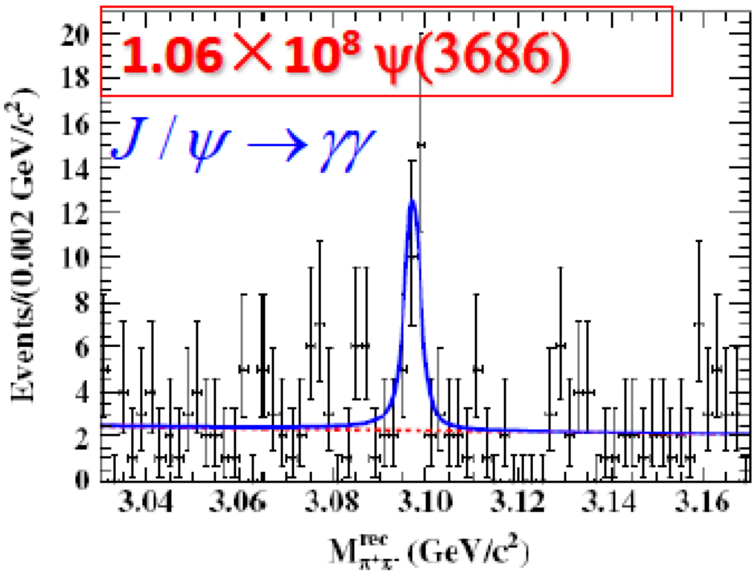
$$\bar{D}^0 \to K^+ e^- \nu_e$$

$$\bar{K}^{*0} \to K^- \pi^+$$

$$Br(J/\psi \to \bar{D}^0 \bar{K}^{*0}) < 2.5 \times 10^{-6}$$

C-parity violation decays

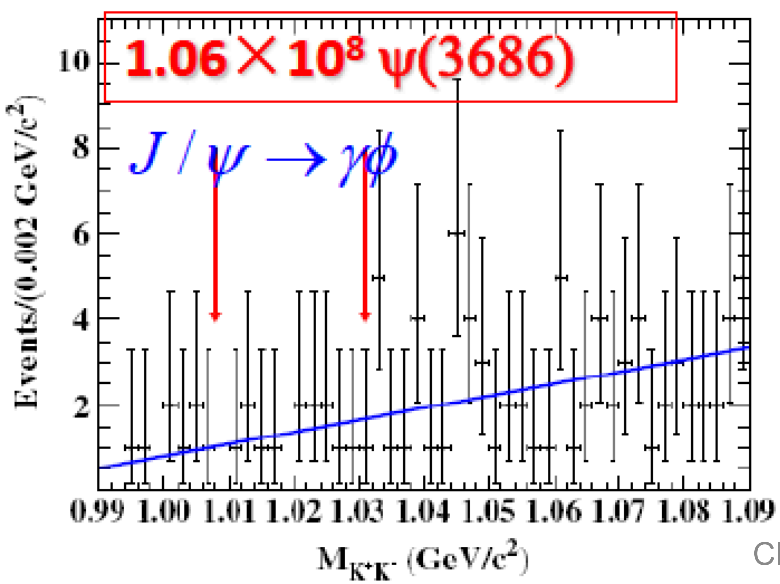
Phys. Rev. D 90, 092002(2014)



The J/ψ→γγ and γφ are studied via ψ(3686)→J/ψ π⁺π⁻

The J/ψ peak in J/ψ→γγ search is dominated by bkg

	$\gamma\gamma$	$\gamma\phi$
N^{obs}	29.2 ± 7.1	0.0 ± 4.6
N^{bkg}	46.5 ± 2.5	negligible
$N^{\mathrm{up}}_{\mathrm{sig}}$ (90% C.L.)	2.8	6.9
ϵ (%)	30.72 ± 0.07	30.89 ± 0.07
$\mathcal{B}(J/\psi \to)$ (this work)	$< 2.7 \times 10^{-7}$	$< 1.4 \times 10^{-6}$
$\mathcal{B}(J/\psi \to)$ (PDG [1])	$< 50 \times 10^{-7}$	–



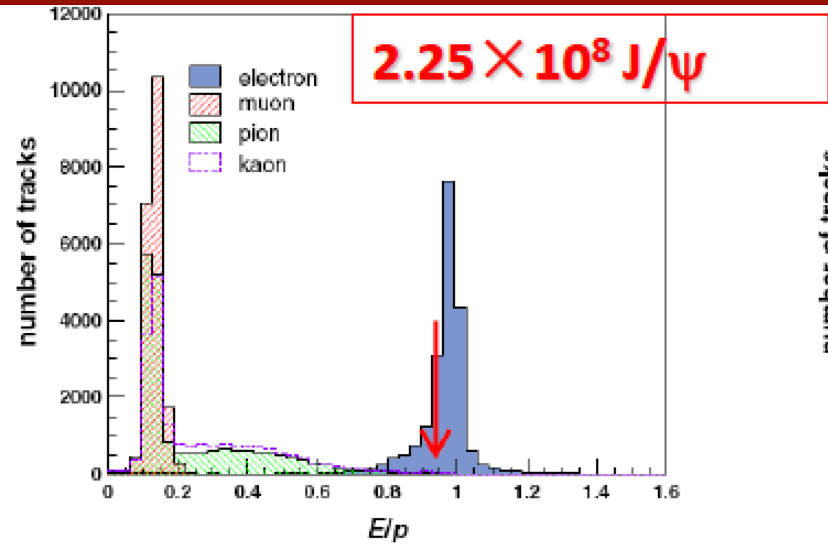
(best results before)

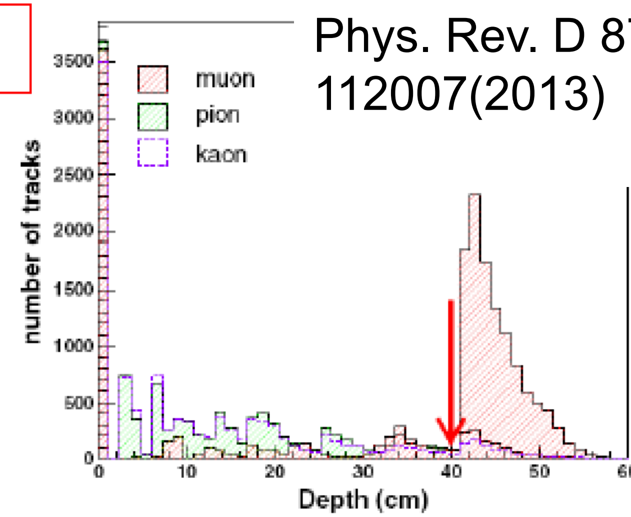
$< 5\times10^{-6}$

$$Br(J/\psi \to \gamma\gamma) < 2.7\times10^{-7}$$

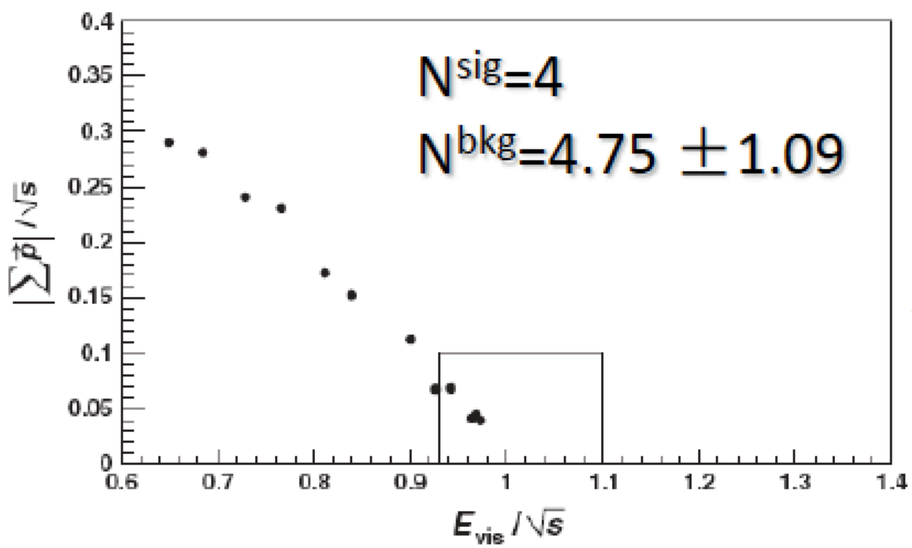
$$Br(J/\psi \to \gamma\phi) < 1.4\times10^{-6}$$

Lepton flavor violation decays





Phys. Rev. D 87, 112007(2013)



$$Br(J/\psi \rightarrow e\mu) < 1.6\times10^{-7}$$

$< 1.1\times10^{-6}$

(best results before)

Summary for Rare Charmonium Decays

- BESIII has studied charmonium rare decays and determined upper limit branching fractions (@90% C.L.) with 225M J/ψ and 106 M ψ(3686):

$Br(J/\psi \to D_s^- e^+ \nu_e + c.c.) < 1.3\times10^{-6}$	$< 3.6\times10^{-5}$
$Br(J/\psi \to D_s^{*-} e^+ \nu_e + c.c.) < 1.8\times10^{-6}$	
$Br(J/\psi \to D_s^- \rho^+) < 1.3\times10^{-5}$	
$Br(J/\psi \to \bar{D}^0 \bar{K}^{*0}) < 2.5\times10^{-6}$	
$Br(J/\psi \to \gamma\gamma) < 2.7\times10^{-7}$	$< 5\times10^{-6}$
$Br(J/\psi \to \gamma\phi) < 1.4\times10^{-6}$	
$Br(J/\psi \to e\mu) < 1.6\times10^{-7}$	$< 1.1\times10^{-6}$

The red numbers show the best results before and others are first measurements.

- 1.3 B J/ψ and 0.5B ψ(3686) events has been collected with BESIII and more searches of charmonium rare decays with better precision can be obtained in near future.

Thank you!